

## WAVELENGTH MANIPULATION SYSTEM AND METHOD

### FIELD OF THE INVENTION

The present invention relates to an optical switching systems and, in particular,  
discloses a wavelength selective switch having possible attenuation control  
5 characteristics.

### BACKGROUND OF THE INVENTION

In optical communications systems, the use of wavelength selective switching  
for applications of optical cross-connects has attracted much interest because of the  
goal of fully flexible, networks where the paths of each wavelength can be  
10 reconfigured to allow arbitrary connection between nodes with the capacity  
appropriate for that link at a particular point in time. Although this goal is still valid,  
it is clear that optical networks will evolve to this level of sophistication in a number  
of stages – and the first stage of the evolution is likely to be that of a reconfigurable  
add/drop node where a number of channels can be dropped and added from the main  
15 path, whose number and wavelength can be varied over time – either as the network  
evolves or dynamically as the traffic demands vary.

This present invention is directed to applications such as reconfigurable optical  
add/drop multiplexer (ROADM) networks and is scalable to the application of  
wavelength reconfigurable cross-connects referred to generically as Wavelength  
20 Selective Switches (WSS).

The characteristics of a wavelength selective element which is ideal for the  
applications of Optical Add/drop and Wavelength selective switching can be  
summarized follows:

- i) scalable to multiple fibre ports

- ii) one channel per port or multiple channels per port operation
- iii) reconfiguration of wavelength selectivity to different grids eg/ 50 GHz or 100 GHz or a combination of both
- iv) low optical impairment of the express path
- 5 v) low losses on the drop and express paths
- vi) ability to add and drop wavelengths simultaneously
- vii) ability to reconfigure between any ports or between any wavelengths without causing transient impairments to the other ports
- viii) equalisation of optical power levels on express path (OADM) or all paths  
10 (WSS)
- ix) provision of shared optical power between ports for a given wavelength (broadcast mode)
- x) flat optical passband to prevent spectral narrowing
- xi) power off configurations that leave the express path of an OADM  
15 undisturbed
- xii) small power and voltage and size requirements.

In reviewing the many technologies that have been applied it is necessary to generalize somewhat, but the following observations can be made.

Two basic approaches have been made for the OADM and WSS applications.

- 20 i) The first has been based on wavelength blocking elements combined with a broadcast and select architecture. This is an optical power intensive architecture, which can provide for channel equalization and reconfiguration of wavelength selectivity, but is not scalable to multiple ports, has very high loss and because of the many auxiliary components

such as wavelength tuneable filters has a large power and footprint requirement.

- 5           ii)   Wavelength switches have been proposed for OADMs, but do not naturally provide for channel equalization, the channel by channel switching in general leads to dispersion and loss narrowing of optical channels, and in the case of multiple port switches it is generally not possible to switch between ports without causing impairment (a hit) on intermediate ports. In addition the channel spacing cannot be dynamically reconfigured. Tuneable 3- port filters have also been proposed having a lack of
- 10           impairment to the express paths but do not scale easily to multiple ports and may suffer from transient wavelength hits during tuning. Tuneable components are usually locked to a particular bandwidth which cannot be varied. In addition poor isolation of tuneable 3 ports means they are less applicable to many add/drop applications which demand high through path
- 15           isolation.

One technology that has been applied to optical cross connects has become known as 3-D MEMs utilises small mirror structures which act on a beam of light to direct it from one port to another. Examples of this art are provided in United States Patents 5,960,133 and 6,501,877. The ports are usually arranged in a 2 dimensional

20   matrix and a corresponding element of the 2 dimensional array of mirrors can tilt in two axis to couple between any one of the ports. Usually two arrays of these mirrors are required to couple the light efficiently and because of the high degree of analogue control required structures based on this technology have proved to be extremely difficult to realize in practice and there are few examples of commercially successful

offerings. In this type of structure, a separate component is required to separate each wavelength division multiplexed (WDM) input fibre to corresponding single channel/ single fibre inputs.

One of the most promising platforms for wavelength routing application relies  
5 on the principle of dispersing the channels spatially and operating on the different wavelengths, either with a switching element or attenuation element. These technologies are advantageous in that the switching element is integrated with the wavelength dispersive element – greatly simplifying the implementation. The trade-off is that in general the switching is more limited, with most implementation  
10 demonstrated to date being limited to small port counts – and the routing between ports is not arbitrary. In general a diffraction grating is used for micro-optic implementations or an Array waveguide grating for waveguide applications. Most of the switching applications have been based on MEMS micro mirrors fabricated in silicon and based on a tilt actuation in one dimension. The difficulty with this  
15 approach has been that to achieve the wavelength resolution required when the angular dispersion is mapped to a displacement. In such cases, an image of the fibre (with or without magnification) is mapped onto the tilt mirror array. In order to couple the light into a second port, additional optical elements are required that convert the angle into a displacement. Different approaches to this have included retroreflection  
20 cubes wedges (US patent 6,097,519) which provide discrete displacements or Angle to Displacement elements (US Patent 6,560,000) which can provide continuous mapping using optical power provisioned at the Rayleigh length of the image. In all of these cases, in order to switch between ports, the tilt mirror needs to pass through the angles corresponding to intermediate ports. In addition, the number of ports is

limited in each of these cases by the numerical aperture of the fiber as each of the different switch positions are discriminated by angles. For a fibre with a numerical aperture of 0.1, a switch which can tilt by  $\pm 12$  degrees could not distinguish 8 different switch positions. One approach that can be used is to decrease the numerical  
5 aperture through the use of thermally expanded cores or micro lenses – but this is done at the expense of wavelength resolution.

An alternative has been to use polarization to switch between ports. Obviously this is most appropriate to switching between 2 ports corresponding to the 2 polarisation states – so is not readily scalable, though more complicated schemes can  
10 be envisaged to allow for switching between multiple ports. With polarization switching, the dynamic equalization of channels can be done at the expense of the rejected light being channelled into the second fibre – so it is not applicable to equalization of the express path whilst dropping a number of wavelengths.

## SUMMARY OF THE INVENTION

15 It is an object of the present invention to provide for an improved form of optical switching system.

In accordance with a first aspect of the present invention, there is provided a wavelength selective manipulation device comprising: at least a first optical input port for inputting an optical signal including a plurality of wavelength channels; a first  
20 wavelength dispersing element for angularly dispersing the wavelength channels of the optical signal into angularly dispersed wavelength signals; an optical power element for focussing in the angularly dispersed dimension the angularly dispersed wavelength signals into a series of elongated spatially separated wavelengths bands; a spatial manipulation element for selectively manipulating the spatial characteristics of

the spatially separated wavelength bands to produce spatially manipulated wavelength bands.

Preferably, the device also includes a first wavelength combining element for selectively combining the spatially manipulated wavelength bands together to produce  
5 a first output signal. The first wavelength dispersing element preferably can include a diffraction grating. The optical power element preferably can include a cylindrical lens and the spatial manipulation element can comprise a liquid crystal display device or spatial light modulator (SLM) acting on the phase of the light.

The SLM device can be divided into a series elongated cell regions  
10 substantially matching the elongated spatially separated wavelength bands. The cell regions each can include a plurality of drivable cells and wherein, in use, the cells are preferably driven so as to provide a selective driving structure which projects a corresponding optical signal falling on the cell region substantially into one of a series of output order modes. The optical power element also preferably can include a  
15 spherical or cylindrical mirror. The diffraction grating can be utilised substantially at the Littrow condition.

In one mode of operation, when the spatial manipulation element is in a first state, first predetermined wavelengths input at the first optical input port are preferably output at a first output port; and when the spatial manipulation element is in  
20 a second state, second predetermined wavelengths input at the first optical input port are preferably output at a second output port. Further, when the spatial manipulation element is in the first state, first predetermined wavelengths input at a third optical input port are preferably output at a fourth output port; and when the spatial

manipulation element is in a second state, first predetermined wavelengths input at the third optical input port are preferably output at the first output port.

In accordance with a further aspect of the present invention, there is provided a wavelength selective manipulation device comprising: a series of optical input and  
5 output ports including a first optical input port inputting an optical signal including a plurality of wavelength channels; a first wavelength separation element for angularly dispersing the wavelength channels of the optical signal into angularly dispersed wavelength signals; a focussing element for focussing in the angularly dispersed dimension the angularly dispersed wavelength signals into a series of elongated  
10 spatially separated wavelengths bands; a spatial manipulation element for selectively manipulating the spatial characteristics of the spatially separated wavelength bands to produce spatially manipulated wavelength bands; the spatially manipulated wavelength bands being subsequently focused by the optical power element and combined in a spatially selective manner by the first wavelength separation element  
15 for output at the output ports in a spatially selective manner.

In accordance with a further aspect of the present invention, there is provided a method of providing wavelength selective separation capabilities for an optical input signal having multiple wavelength components, the method comprising the steps of:  
(a) projecting the optical input signal against a grating structure so as to angularly  
20 separate the wavelength components; (b) focussing each of the wavelength components in the wavelength dispersed dimension (vertical) into an elongated wavelength component element; (c) independently manipulating the elongated wavelength component element; (d) combining predetermined ones of the manipulated elongated wavelength components.

- The focussing step preferably can include utilising a cylindrical lens and spherical mirror to focus the wavelength components. The step (c) preferably can include utilising a liquid crystal display device to separately manipulate each of the wavelength components. The liquid crystal display device can be divided into a series
- 5 elongated cell regions substantially matching the elongated wavelength components. The cell regions each can include a plurality of drivable cells and wherein, in use, the cells are preferably driven so as to provide a selective driving structure which projects a corresponding optical signal falling on the cell region substantially into one of a series of output order modes.
- 10 In accordance with a further aspect of the present invention there is provided a wavelength selective manipulation device comprising: at least a first optical input port for inputting an optical signal including a plurality of wavelength channels; polarisation alignment element for aligning the polarisation state of the optical signal; a wavelength dispersion element for angularly dispersing the wavelength channels of
- 15 the optical signal into angularly dispersed wavelength signals; an optical power element for focussing in the angularly dispersed wavelength signals into a series of elongated spatially separated wavelengths bands; a spatial manipulation element for selectively spatially manipulating the characteristics of the spatially separated wavelength bands to produce spatially manipulated wavelength bands.

20 BRIEF DESCRIPTION OF THE DRAWINGS

Preferred forms of the present invention will now be described by way of example only with reference to the accompanying drawings in which:

Fig. 1 illustrates schematically a side perspective view of the preferred embodiment;



Fig. 2 is a schematic top plan view of the arrangement of the preferred embodiment;

Fig. 3 illustrates schematically the operation of reflective modes;

Fig. 4 illustrates schematically the arrangement of cells on a Liquid Crystal

5 Display device;

Fig. 5 – Fig. 9 illustrate various driving arrangements for producing different diffractive orders;

Fig. 10(a) to Fig. 10(d) illustrates the driving arrangement for an AC driving of a Liquid Crystal type display;

10 Fig. 11 illustrates schematically a further alternative embodiment of the present invention; and

Fig. 12 illustrates the optical beam profile along the optical arrangement of Fig. 11

#### DESCRIPTION OF PREFERRED AND OTHER EMBODIMENTS

15 In the preferred embodiment, an arrangement is provided for each wavelength of light to be dispersed and focused in one axis and collimated in the orthogonal axis such that a mode selecting liquid crystal array or spatial light modulator can be utilised to select between the various orders of the reflective or transmissive diffraction grating as established by the liquid crystal operating on one polarisation  
20 state of light. As is well known, for a collimated beam an angular deflection of the beam such as that obtained by changing the order of a reflective diffraction grating will have the effect of translating the focus of the beam. If the optical train is established to be telecentric then this translation is achieved without affecting the coupling efficiency and so can be coupled effectively into a second port located at a

given translation from the first post such as would be provided in the case of a fibre array

Turning initially to Fig. 1, there is illustrated schematically a side perspective view 11 of the arrangement of the preferred embodiment. An array in the x-dimension of optical input output fibres 1-10 is initially provided with the initial input being  
5 along the fibre 3. Each of the fibres can have thermally expanded core ends. The emitted light from core 3 is assumed to be of a single vertical polarisation only (If required, a polarisation alignment means (not shown) can be utilised to obtain the single polarisation light in a known manner). The light is projected to a spherical  
10 mirror 12 where it is reflected and collimated before striking a diffraction grating 14. The diffraction grating 14 is arranged at the Littrow condition. At the Littrow condition, as is known in the art, the reflected light is angularly dispersed in the y axis into its spectral components.

The light emitted from the grating 14 will have an angular separation in  
15 accordance with wavelengths. The spectral components are reflected back through the cylindrical lens 13 having optical power in the x dimension. The spectral components are focussed in the x dimension near to the mirror 12 but remains collimated in the y dimension. Upon return through the cylindrical lens 13 the spectral components are now collimated in the x dimension but continue to converge in the y dimension so as to  
20 focus in that dimension on or near an active or passive Liquid Crystal Display (LCD) device 14 providing a series of elongated spectral bands.

For clarity of understanding, Fig. 2 illustrates a top plan view of the arrangement of Fig. 1. Where the light striking the Liquid Crystal Display 15 undergoes pure reflection, the light traverses the return path 20-23 where it again

strikes the grating 14 at the Littrow condition where it is recombined with other frequencies and follows a return paths 26-28 where it passes to output port 8.

The Liquid Crystal Display device 15 can be of an active or passive type with a series of independently controllable areas. It is assumed that the reader is well aware of the understanding of Liquid Crystal Display devices and their operation can be entirely standard. In the first preferred embodiment it is noted that the LCD can be essentially equivalent to that used in Spatial Light Modulators (SLM), in particular a phase only reflective SLM such as that demonstrated by Boulder Nonlinear systems using CMOS technology. The design of the CMOS back plane is readily adapted to the pixel size requirements as would be apparent to one skilled in the art.

In the preferred embodiment we use a reflective LCD device and we illustrate for the case of selection between a purely reflective and 4 different diffraction states. The proposed structure is also designed to achieve high extinction between the selected order and the other orders and also the reflective state. This is achieved by the use of symmetry to ensure that at each of the modes not selected or the purely reflective state the integral of the phase of the components goes to zero in theory. Although higher order diffractions can be excited with some efficiency proper choice of cell size (which determine the slit diffraction numerical aperture) can limit this to small fractions and achieve high through- put.

The order-selection mechanism relies on varying the retardation in the sub cells of the induced grating structure in a way that achieves the necessary selectivity and extinction. In this example a simplified drive is achieved by the use of only 4 levels:

State 0 :  $4 \lambda/8$  retardance

State 1 :  $3\lambda/8$  retardance

State 2 :  $2\lambda/8$  retardance

State 3:  $\lambda/8$  retardance

Ideally, the reflected light from the LCD is controlled so that different  
5 diffraction orders correspond to different angles of propagated light. In the example  
given, the first order of diffraction is assumed to be at 0.0955 degrees. By controlling  
the Liquid Crystal Display device, selective excitation of the positive or negative first  
order of diffraction line can be achieved. This corresponds to a spatial periodicity of  
377.5  $\mu\text{m}$ . Hence, as illustrated in Fig. 4, the diffraction line 40 is assumed to be  
10 377.5  $\mu\text{m}$  in length and is divided into 8 cells 41 with each cell being approximately  
42  $\mu\text{m}$  in length. This can be readily achieved utilising standard lithographic  
techniques for the electrode structure.

In a first embodiment, the Liquid Crystal Display device is utilised to form a  
reflective diffraction grating such that, as illustrated in Fig. 3, input light 30 is output  
15 selectively either in a fully reflective manner 31, to the first order 32, 33 or to the  
second orders 34, 35.

The cells of the Liquid Crystal structure can be driven so as to select the output  
order. Fig. 5 – Fig. 9 illustrates one form of the various possible driving  
arrangements for the 8 cells. In a first arrangement in Fig. 5, designed to produce a  
20 0.0955 first order deflection, the driving state can be as illustrated 52 with the states  
being 0,0,1,1,2,2,3,3. In Fig. 6, for the negative first order 60, the driving states can  
be 3,3,2,2,1,1,0,0. In Fig. 7, for the second order output 70, the driving states 71 can  
be 0,1,2,3,0,1,2,3. Next in Fig. 8, for the negative second output order 80, the driving

states 81 can be 3,2,10,3,2,1,0. Finally, in Fig. 9, for the purely reflective state 90, the driving state 91 can be all 0's.

Each of these modes can then be used in the arrangement of Fig. 1 and Fig. 2 to couple between different input 1-5 and output 6-10 fibres. At wavelengths where the selected LCD mode is in the pure reflective state (0 degrees), the coupling is as follows

Fibre 1 to fibre 10

Fibre 2 to fibre 9

**Fibre 3 to fibre 8 (express path in to out)**

10 Fibre 4 to fibre 7

Fibre 5 to fibre 6

At wavelengths where the selected mode is +0.0955 degrees, the wavelength from fibre 3 is now coupled to drop fibre 7 as seen below

Fibre 1 to fibre 9

15 **Fibre 2 to fibre 8 (add path)**

**Fibre 3 to fibre 7 (drop path)**

Fibre 4 to fibre 6

At wavelengths where the selected mode is -0.0955 degrees, the wavelength from fibre 3 is now coupled to drop fibre 9

20 Fibre 2 to fibre 10

**Fibre 3 to fibre 9 (drop path)**

**Fibre 4 to fibre 8 (add path)**

Fibre 5 to fibre 7

At wavelengths where the selected mode is +0.1910 degrees, the wavelength from fibre 3 is now coupled to drop fibre 6 as seen below

**Fibre 1 to fibre 8 (add path)**

Fibre 2 to fibre 7

5      **Fibre 3 to fibre 6 (drop path)**

Fibre 4 to fibre 5

At wavelengths where the selected mode is -0.1910 degrees, the wavelength from fibre 3 is now coupled to fibre 10 as seen below

**Fibre 3 to fibre 10 (drop path)**

10      Fibre 4 to fibre 9

**Fibre 5 to fibre 8 (add path)**

Fibre 6 to fibre 7

Selective attenuation of a particular wavelength channel can be achieved by attenuation of the individual coupling efficiency into modes and having a separate order which is used only for attenuation and is selectively excited at the expense of the efficiency of the selected order. In this way, the power at the selected order can be adjusted to a desired level. Additionally, a diffraction order can be used for monitoring purposes. Light can be coupled at one wavelength into the additional diffraction order – received on a photo detector and used as a monitor or control mechanism for the power levels in the system. This light could be collected by the addition of a fibre (single or multimode).

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It is easy to generalize the principles here to other numbers of orders as required.

In a second further embodiment, the diffraction orders be addressed in a simple way and an electrode structure and driving scheme is proposed that can achieve this simply – though many alternative implementations are possible and the scope of the invention is not limited in any way to this method.

5 In the y-axis in which the wavelengths of light are resolved, one of 5 voltage functions  $F_{yi}(t)$  is applied to the electrode corresponding to the mode we wish to excite. Each of the electrodes corresponding to the subcells in the x-axis have voltage functions  $F_{xj}(t)$ . The voltage function is chosen such that the relationship between the top and bottom electrodes ( $F_{yi}(t)-F_{xj}(t)$ ) for each of the subcells cells produces an AC  
10 component with a corresponding retardance to that required for the particular mode.

The exact form of these functions will depend on the linearity and frequency dependency of the exact liquid crystal used. To exemplify the approach a linear voltage retardance response and no frequency dependence is assumed.

In this case, the modes can be produced by using four different driving  
15 frequencies for the different orders of the induced grating. Each of the subcell electrodes is driven by a combination of the four frequencies with equal magnitude but a phase chosen to give  $F_{yi}(t)-F_{xj}(t)$ , the correct AC component to achieve the required retardance. For example, when the phase of the drive frequency and the phase of the corresponding frequency component of the subcell is in phase there is no  
20 contribution to the AC voltage (with the only contribution being for the 2<sup>nd</sup> to 4<sup>th</sup> frequency components which is equal for all subcells and provides a bias voltage). Equally when the phase of the drive frequency and the phase of the corresponding frequency component of the subcell are  $\pi$  out of phase, then the AC component is a maximum. In this case the maximum AC component is chosen to achieve a

retardance of  $\pi/8$  and the minimum AC component is chosen to achieve a retardance of  $\pi/2$ . The two other states ( $\pi/4$  retardance and  $3\pi/8$  retardance) are achieved by phase delays in the corresponding subcells of  $\pi/3$  and  $2\pi/3$ . So by control of the drive frequency and phase of  $F_y$  it is possible to choose between one of the four diffraction  
5 modes. When  $F_y$  is zero then the retardance of each subcell is equal so the induced grating is in a purely reflective state. Fig. 10(a) to Fig. 10(d) illustrate the corresponding driving arrangements. By using frequency components of 1kHz, 2kHz, 4kHz and 8kHz, each of the modes can be successfully driven to give a desired structure of the subcells. Similar approaches have been used to achieve grey level  
10 modulation in passive matrix displays by modulating in such a way as to create the correct RMS voltage level for the grey level being modulated.

In a third embodiment the same objective is achieved efficiently employing a micro arrays of cylindrical lenses. The arrangement can be as illustrated in Fig. 11

In this case, there is provided an input array (in the x axis) of 2 fibres (101 and  
15 102) and output array of 2 fibres (103 and 104) with a fibre spacing of 250 microns. The output of the fibres is coupled into a first micro cylindrical lens (110) to modify the divergence of the beam. The output is then coupled into an x-axis array of cylindrical lenses (111) with a separation corresponding to the fibre separation. The focal length of the lens 111 is chosen to be 500 micron so as to form a collimated  
20 beam of approximately 100 micron diameter. This beam is split in the x direction into two polarization states by a walk off crystal (112) of thickness 1.25 mm and then equalized in polarization by the polarization diversity optics 113 which can comprise an array of waveplates having a spacing of 125 microns. The output from the waveplates 113 consists of polarisation aligned beams. The waveplates can be



produced by nano-optic lithographic techniques (as supplied by NanoOpto of Somerset, New Jersey) or by an arrangement of standard quartz waveplate techniques.

Each of the output beams is then is projected to a first x-axis cylindrical lens 114 with a focal length of 5 cm which provides collimation in the x axis followed by a y axis cylindrical lens (115) with a focal length of 20 cm. Next the beams are reflecting from a grating (116) ( 1200 l/mm) at the near Littrow configuration. After the second pass of the x cylindrical lens the now diffracted beam resulting from the 100 micron diameter beam is collimated in the x direction – the combined effect of the double pass of the lens 115 and reflection from grating 116 being a compound reflective lens with focal length of approximately 10 cm.

The image of the reflected fibre is focused in the y direction by the y cylindrical lens producing a y focused but x-collimated beam. Typically the size of the beam at this point is highly asymmetric with radial dimensions of 20 microns in y and approximately 700 microns in x dimension. The image is wavelength dispersed in the y dimension and the individual channels can be accessed by a liquid crystal spatial light modulator (SLM) (118) after being folded down by a prism (117) to allow simple mounting of the SLM.

The SLM (118) is again able to direct the image of the light from input fibre (102) between the fibre drop port(103) or express port (104) by selection of the correct order of the induced grating when the light retraces its path through the system. Simultaneously, when the input light is directed to the drop port at a particular wavelength, the same wavelength will be directed from the add port (101) to the express port (104)

The reimaged light at the fibre port is again largely circular symmetric as the effects of the cylindrical lenses are reversed through the return propagation . Further, channel by channel attenuation control of optical power can be achieved by exciting a fraction of the power into an angle that doesn't correspond to an active port thereby  
5 attenuating the power in the chosen path.

The grating element (116) can be designed to reduce the x angular dependence of the grating by the use of a wedged prism which has an opposite angular dependence.

Further, the first cylindrical lens 114 can be replaced with a reflective  
10 cylindrical lens if a more compact design is desired without departing from the scope of this invention – though for clarity a transmissive cylindrical lens system has been described.

Turning now simultaneously to Fig. 12 and Fig. 11, there is illustrated the optical profile at various points along the optical pathway. The point 210 corresponds  
15 to the optical profile of the beams emitted fibres e.g. 110. The profile 213 corresponds to the optical profile of the light emitted from the element 113. Here the separate polarisation are split due to the waveplate 112. The profile 214 corresponds to the light emitted from the lens 114. The profile 215 corresponds to the light emitted from the lens 115 and the profile 217 corresponds to the light striking the SLM device 117,  
20 118.

The foregoing describes preferred embodiments of the present invention. Modifications, obvious to those skilled in the art can be made thereto without departing from the scope of the invention.